

Performance Study of an 8-story Steel Building Equipped with Oil Damper Damaged During the 2011 Great East Japan Earthquake

Part 2: Novel Retrofit Strategy

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Abstract

In this paper, the full rehabilitation process of a damaged passively controlled building is reported. A hybrid retrofit plan that uses tin-rubber bearings to replace the damaged oil dampers is proposed and tested within the size requirement and cost budget. Structural Identification and nonlinear dynamic analyses have been conducted to verify the effectiveness of the hybrid retrofit plan. After the rehabilitation was completed, the retrofitted building with tin-rubber isolators is proved by a recent earthquake to have a better seismic performance than the original building with oil dampers. Finally, the performance of the damping system will be discussed in this paper based on the performance-based design concepts. The performance level of the energy dissipation devices should be set accordingly based on the building performance level for the seismic rehabilitation design. The safety issues of the structural frame and retrofit procedure after the failure or degradation of the damping devices should be investigated in the future.

Keywords: isolator; oil damper; retrofit; the 2011 Great East Japan Earthquake

1. Introduction

Passive energy dissipation devices are applied more and more frequently since they were introduced to civil engineering in the mid-1990s. After being tested by several major earthquakes, they may be trusted to protect human life and properties. Usually, passive energy dissipation devices are believed to be safe during earthquakes and will continue to function after major earthquakes. However, this belief has been questioned by a series of failure events involving passive energy dissipation devices during the historic Great East Japan Earthquake on March 11th, 2011 (also known as the 3/11 Earthquake).

Shortly after the 3/11 Earthquake, the Japan Society of Seismic Isolation (JSSI) investigated the condition of the passive-controlled structures, including the buildings with base isolation and supplemental damping devices. While no superstructure failures were reported, numerous failures in the expansion joints and significant failures of the lead dampers for the base-

isolated buildings have been investigated and reported (JSSI, 2012). Kasai *et al.* also reported that cracks in the lead dampers used for base-isolated buildings were observed after the 3/11 Earthquake (Kasai *et al.*, 2013).

Cao *et al.* reported the failure event during the 3/11 Earthquake of a passive control system installed in Administration Building (Cao *et al.*, 2012), which is located on the main campus of Tohoku Institute of Technology in Sendai, Japan. Previously, the authors investigated how and why the oil dampers of this building were devastated by the unprecedented earthquake (Xie *et al.*, 2015). The deficiency of the stroke limit caused the dampers to pound repeatedly against the connection on the floor and finally wrecked the passive dampers on the first floor.

This article aims to report the full rehabilitation process for the damping equipment. This process includes the selection of a retrofit plan, installation and construction work, and verification by real earthquakes. Extensive nonlinear time-history structural analyses have been performed to determine the appropriate retrofit strategy for replacing the damaged oil-dampers. Finally, a hybrid concept of vibration control is determined using rubber bearings to replace the damaged dampers on the first floor because the rubber bearings are capable of accommodating the large interstory drift induced by the 3/11 Earthquake. Although numerical simulations show the effectiveness

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of the selected equipment, verification by real earthquakes is still believed to be necessary. A moderate earthquake vibrated the retrofitted building after the rehabilitation work, and the retrofit strategy proved to have a better seismic performance in comparison with the original one, which was equipped with oil dampers, before the 3/11 Earthquake.

More importantly, a series of failure events evidenced that the damping devices could be damaged by the most infrequent and intensive earthquakes. This failure is raising an alarm that the consequences of a damping system failure should be considered during the initial design of a passively controlled building. After earthquakes, the main frame with the damaged devices should be able to survive the coming aftershocks without causing significant casualties and economic losses. In addition, the damping system should be able to be repaired or replaced immediately to restore or enhance the performance of the structure. For this situation, the proposed retrofit process in this paper is believed to be important because it shows a hybrid concept of vibration control and provides a quick and inexpensive retrofit strategy.

2. Building Description and Damage Event

The eight-story Administration Building on the main campus of the Tohoku Institute of Technology (in Sendai, Japan) was constructed in 2003 and has a length of 48 m, a width of 9.6 m, and a height of 34.2 m, as shown in Fig.1. The superstructure is a steel-frame structure with precast concrete slabs, and the one-story basement is reinforced concrete. To verify the effectiveness of the newly developed oil damper at the Tohoku Institute of Technology and to improve the structural earthquake resistance capability, 56 sets of dampers were installed, as shown in Fig.1. Each floor has eight sets of oil dampers, which are connected with the use of V-type braces between the adjacent floors. The first and the second floors are merged to form a large space with a height of 8 m.

During the 3/11 Earthquake, all eight sets of dampers on the first floor were destroyed. The damper pistons on both sides were torn apart from the central cylinder (oil container). The U-type abutments fixed on the first floor were opened wider as the pistons exceeded the stroke limit and cushion limit and pounded against the abutments. Sixteen sets of dampers on the third and fourth floors had severe oil leakages due to the failure of the sealing material, even though the mechanical parts of the oil dampers remained undeformed. The details of the damage event and numerical simulation can be found in Part 1 of this paper (Xie *et al.*, 2015).

3. Retrofit Principle

Although the damping system of the 8-story steel building was severely damaged by the earthquake, there was no other structural damage found in the main frame after quick safety evaluation. The building was reopened

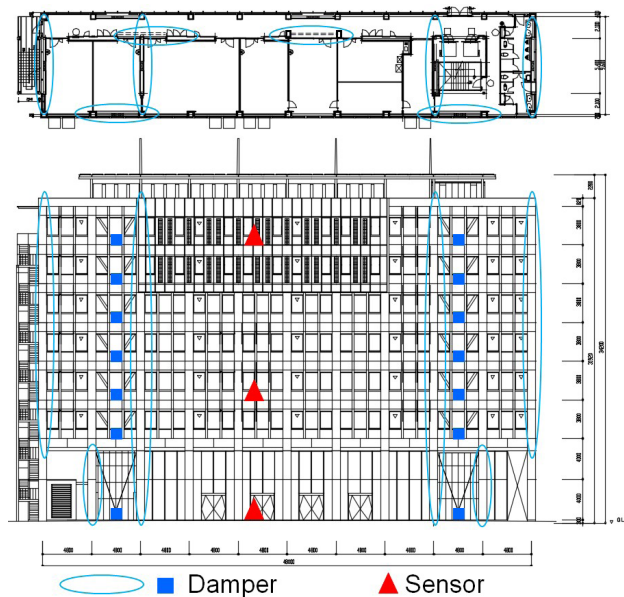


Fig.1. Administration Building of Tohoku Institute of Technology and Damper Allocation

to the public with the damaged dampers removed. However, the vacant connection between the V-type brace and the U-type abutment caused visually unpleasant feelings and psychological panics in the public. The school board decided to retrofit these damaged dampers.

As mentioned in Part 1, this is the first publicly reported failure event of a passively controlled building in the world. There are currently no existing guidelines or building codes that could be referred to retrofit a damaged passively controlled building, and the work group confronted other difficulties as well. There was a budget problem right after the 3/11 Earthquake because the university was short of funding for the structure rehabilitation. Secondly, the connecting space between the brace and the abutment was limited.

Therefore, the decisions concerning retrofit plans were very difficult to make. The school board proposed four principles for selecting new damping devices for the rehabilitation of this Administration Building:

1. Having enough capability to resist the same magnitude earthquake as the 3/11 Earthquake;
2. High cost efficiency within the rehabilitation budget;
3. Suitable for the connecting space without massive alteration or construction work;
4. Having better performance in comparison with the original oil damper if possible.

According to different damage scenarios for the oil dampers on the 1st, 3rd and 4th floors, different retrofit solutions were adopted. For the dampers on the 3rd and 4th floors, while the mechanical parts remained undeformed during the 3/11 Earthquake, the oil leakage happened due to the wearing out of the sealing material. For budgeting control, the oil dampers were reassembled in the factory to replace the worn-out sealing polymer and refill the viscous oil in September 2012.

A different solution should be taken to address the retrofit of the dampers on the 1st floor. Obviously, it was not appropriate to reinstall dampers with the same performance level as the damaged ones because the dampers would be destroyed again by the same magnitude earthquake. A better choice would be to find a retrofit plan that would enhance the performance level of the dampers. Oil dampers capable of larger interstory drifts with a larger size were eliminated as well because there is neither enough financial support nor enough space for installation. The idea to develop an oil damper having a suitable size with higher performance was also eliminated because there is neither enough financial support nor enough time.

4. Retrofit Design and Simulation

The numerical model of this steel building is developed using SAP2000. All the structural members, such as beams, columns, and so on, are modelled according to their actual size. The oil dampers are modelled by the link elements representing the simplified and typical load-displacement curves. Some undetermined parameters of the numerical model are defined via identification before and after the 3/11 Earthquake, as described in Part 1 (Xie *et al.*, 2015). Extensive nonlinear time-history structural analyses have been performed to determine the appropriate retrofit strategy for replacing the damaged oil dampers. In the beginning, various ready-made oil dampers with a suitable size for installation were tested using a nonlinear dynamic simulation that incorporated the proper velocity-force mathematical model for the link elements of the dampers. Unfortunately, the simulated relative displacement between the first and third floors exceeds their allowable stroke limits under the vibrations of the 3/11 Earthquake.

The retrofit concept was then changed by taking into account other types of supplemental damping devices, such as laminated rubber bearing (isolators), in addition to oil dampers. Several isolators with different cross sections, which have enough capability to sustain the large interstory drift induced by the 3/11 Earthquake, have been tested via simulation. Among these candidate solutions, tin-rubber bearings, which have the advantage of a low cost, were selected to replace the damaged oil dampers on the first floor.

The diameter of the tin-rubber bearing is 300 mm, and the height including the steel flange is 166.5 mm. The elastic displacement limit of the tin-rubber bearing is 120 mm, and the ultimate displacement limit is 400 mm. Unlike the conventional use of rubber bearings as vertical supporters to decouple the superstructure from the ground motion, the energy dissipation capability of the rubber bearings subjected to a little vertical pressure is directly utilized for this proposed seismic rehabilitation. Fig.2. shows the dimension of the selected isolator, and Fig.3. plots the hysteresis curve of the isolator between the load and the displacement.

The hysteresis curve, which was tested in the factory, was used for the dynamic simulation in this paper. K_1 is the initial stiffness of the rubber bearing, K_2 is the post yield stiffness (400kN/m), Q_d is the intercept point where the ideal post-yield curve intersects with the y-axis of the coordinate system (42kN), K_{eq} is the equivalent stiffness of the bearing (820kN/m), δ_1 is the design displacement amplitude of the rubber bearings (100 mm), and H_{eq} is the equivalent damping ratio (0.27). The rubber bearing is modelled by a link element in SAP2000, with a stiffness as K_1 , a yield strength as Q_d , and a post-yield stiffness ratio as K_2/K_1 .

The acquisition system installed in this building did not work during the 3/11 Earthquake because of a power blackout. Therefore, the ground motion captured by an observation station 50 meters away from this building is used as the ground excitation for the simulation of the main shock on March 11, 2011, as shown in Fig.4. (the recorded PGA is 354 gal in EW direction and 280 gal in NS direction).

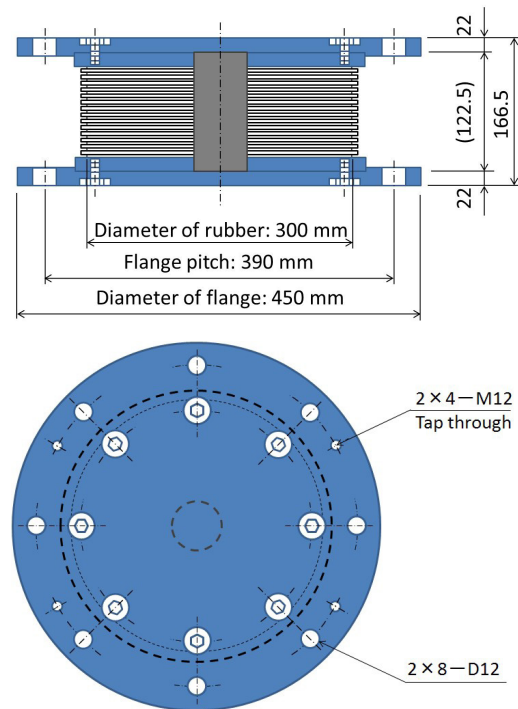


Fig.2. Dimension of Tin-Rubber Bearing

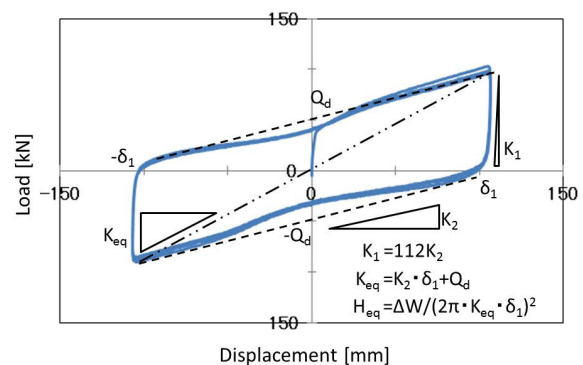


Fig.3. Hysteresis Curve of Tin-Rubber Bearing

For the first floor of the building, based on the simulation results, a set of double-connected bearings is suggested to replace one oil damper in EW direction, and a single rubber bearing replaces one oil damper in NS direction. Fig.5. shows the simulated acceleration response (in both EW and NS directions) of the structure with tin-rubber isolators under the 3/11 Earthquake, and is compared with the responses of the original building equipped with oil dampers, in which the identified model before the 3/11 Earthquake is used for the dynamic simulation. The blue line indicates the response of the building retrofitted with tin-rubber isolators, whereas the red line represents the original building with oil dampers. The peak acceleration responses in both directions on the fourth floor of the retrofitted structure are smaller than that of the original structures with oil dampers. In addition, the acceleration responses are suppressed more in EW direction than in NS direction because of the double deployment of the isolators in EW direction. This implies the possibility and effectiveness of the proposed retrofit plan with isolators.

Fig.6. shows the simulated relative displacement responses between the 1st and 3rd floors of the buildings with isolators or dampers during the 3/11 Earthquake. Similarly, the proposed retrofit scheme has smaller displacement responses than the case using oil dampers, and less relative displacements are achieved in EW direction than in NS direction. The maximum interstory drift of the retrofit plan is no more than 100 mm, which is still within the displacement limit of the tin-rubber bearings, while the maximum interstory drift of the original building with oil damper configuration was over 60 mm in both directions, far beyond the destructive limit displacement of the oil dampers. The deformation capability of the tin-rubber isolators is vastly superior to that of the oil dampers.

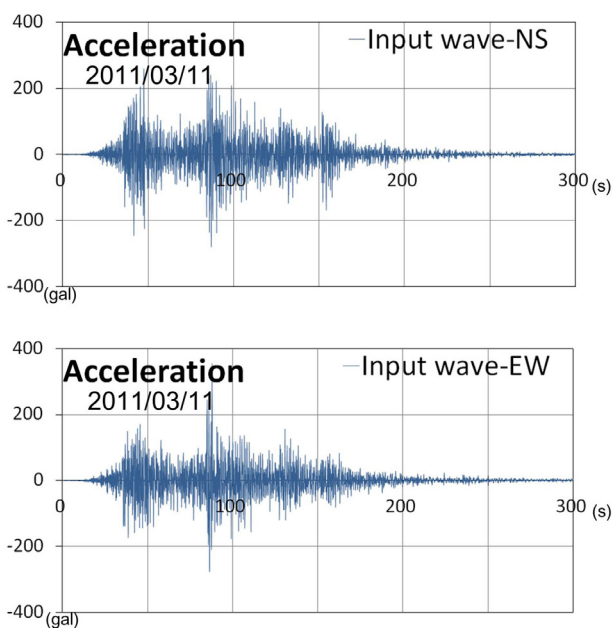


Fig.4. Ground Motion of 2011/03/11

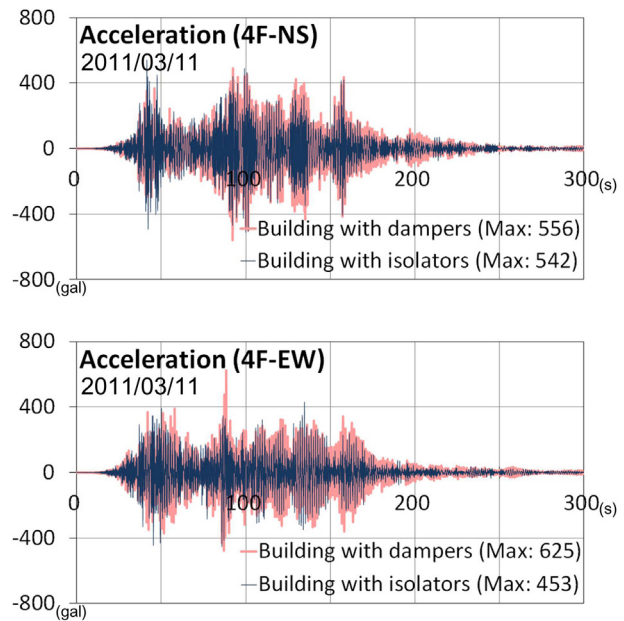


Fig.5. Acceleration Response of Simulation (2011/03/11)

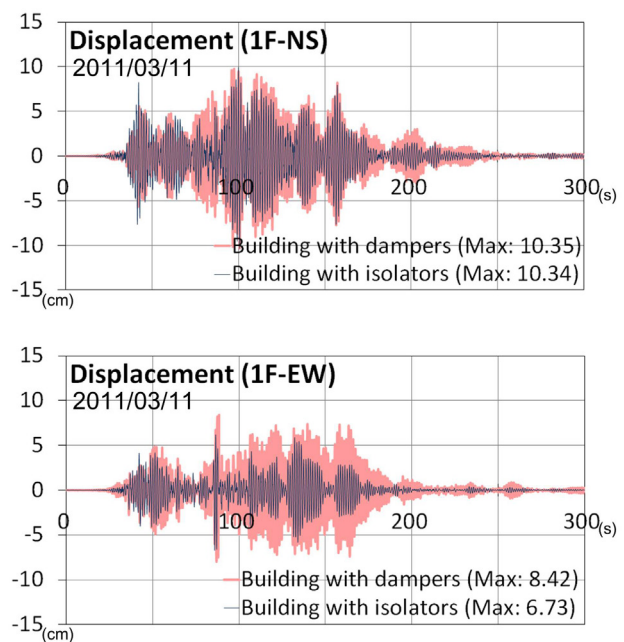


Fig.6. Displacement Response of Simulation (2011/03/11)

In terms of displacement and acceleration results, the proposed retrofit scheme has a better performance than that of the original energy dissipation system, which verifies the effectiveness and validity of replacing the damaged oil dampers with isolators.

Utilizing the simulated responses, the transfer functions between the fourth and the first floors can be obtained by spectrum methods, as shown in Fig.7. The maximum amplification factors for the isolator case are smaller than those for the damper case at the dominant resonant periods. The resonant periods of the retrofitted building are changed slightly, which is the result of the additional stiffness provided by the isolators.

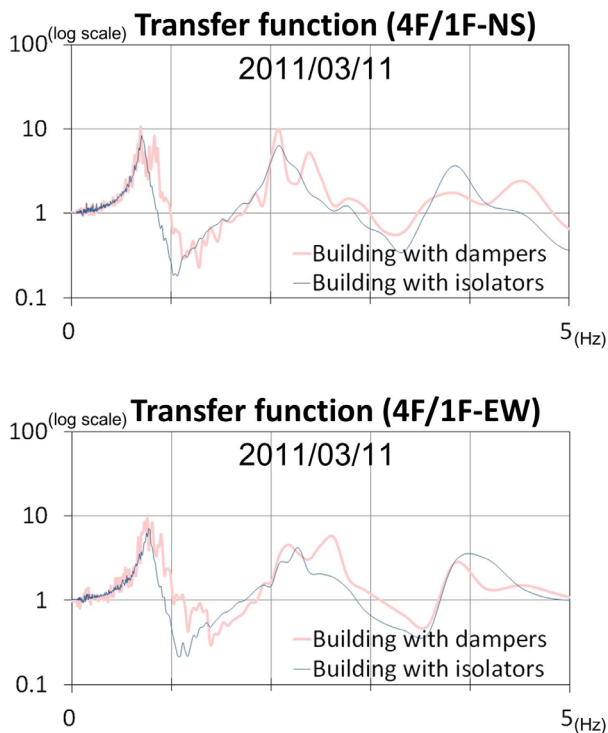


Fig.7. Transfer Function of 4F/1F (2011/03/11)

5. Different States of the Building

The reassembled oil dampers for the 3rd and 4th floors were reinstalled in Sep. 2012, and the installation of the tin-rubber bearings was completed in the middle of Feb. 2013. The original oil dampers from the 5th to 8th floors were kept unchanged. This steel building was retrofitted with a hybrid vibration control mechanism, as pictured in Fig.8.

The building has experienced damage, rehabilitation and verification periods. The structure can be summarized as undergoing five different states with specific dynamic characteristics in sequence. For each building state, a structural identification was conducted to fit the observed responses so as to establish the suitable finite element model. The identification process referred to was presented in previous paper by the authors (Xie *et al.*, 2015).

1st state = Original state before 2011/03/11: Original state refers to the building before the 3/11 Earthquake. The record of 2011/03/09 (with a PGA of 32 gal in EW direction and 26 gal in NS direction) is used for the structural identification.

2nd state = 3/11 Earthquake state: It is the building state when the 3/11 Earthquake struck.

3rd state = 1st floor dampers damaged and oil leakage on the 3rd and 4th floors, from 2011/03/11 to 2012/09/19: It is the building state with the damaged oil dampers on the 1st floor and oil leakage of dampers on the 3rd and 4th floors. The record of 2011/04/07 (with a PGA of 176 gal in EW direction and 289 gal in NS direction) is used to identify the structure in the 3rd state.

4th state = 1st floor dampers damaged from 2012/09/19 to 2013/02/15: The repaired oil dampers on the 3rd and 4th floors were reinstalled on 19th September 2012, while dampers on the 1st floor remained damaged. The building response on 2012/12/07 (with a PGA of 41 gal in EW direction and 50 gal in NS direction) is used for the structural identification in the 4th building state.

5th state = retrofitted state from 2013/02/15: On 15th February 2013, the retrofit was completed with rubber bearings replacing the damaged oil dampers on the 1st floor. Half a year after the retrofit, an earthquake attacked Sendai City (with a PGA of 38 gal in NS direction and a PGA of 32 gal in EW direction) on 4th August 2013.

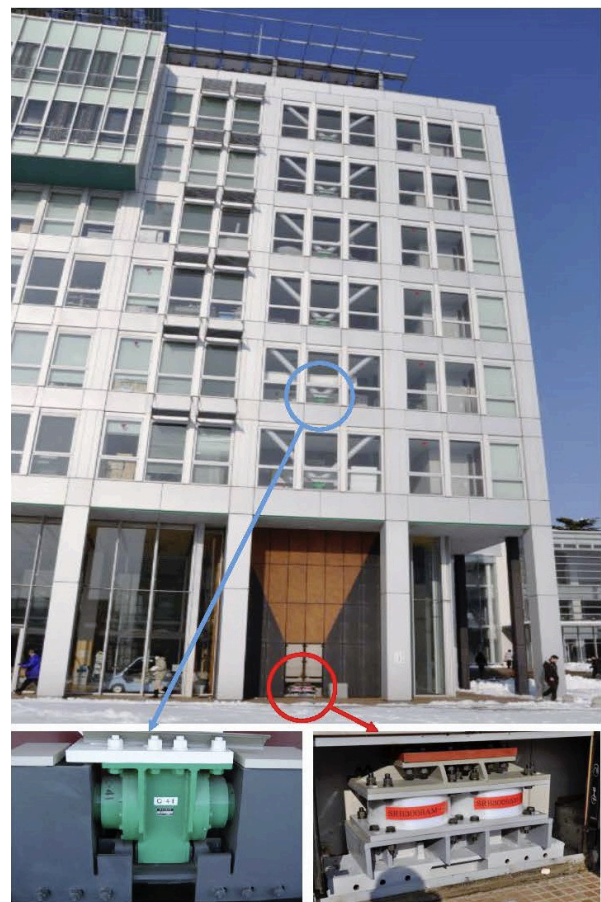


Fig.8. Retrofitted Building with Isolators on the 1st Floor and Oil Dampers on the 3rd ~ 8th Floors

6. Effectiveness Verified by Earthquake

After the construction work, the effectiveness of the proposed retrofit method is waiting to be verified by a real earthquake with a moderate seismic intensity. Although many earthquakes have occurred since the middle of Feb. 2013, the verification process was not completed until Aug. 2013.

On August 4, 2013, a moderate earthquake (Miyagi Oki Earthquake, M6.0) occurred near Sendai City. It was the first time that the responses of the building were recorded after isolator installation because

seismometers can only be triggered when the ground acceleration exceeds a certain threshold. The ground motion of 2013/08/04 has a PGA of 38 gal in NS direction and a PGA of 32 gal in EW direction, as plotted in Fig.9.

The identification process was performed to rebuild the numerical model for the dynamic simulation of the retrofitted building. Fig.10. shows the comparison of the acceleration responses on the 4th floor in both directions between the observation and simulation of the building on 2013/08/04. The difference between the measured and simulated responses is tolerable.

Transfer functions calculated by spectrum methods are depicted in Fig.11. for both cases on 2011/04/07 (i.e., the damaged state after the 3/11 Earthquake) and on 2013/08/04 (i.e., the retrofitted state). In the state of the building on 2011/04/07, the dampers of the 1st floor were all destroyed, and the oil dampers on the 3rd and 4th floors had leaked, as reported in Part 1. The maximum amplification factor on 2013/08/04 at the dominant resonant periods decreased in comparison with the state on 2011/04/07. The retrofitted structure has shorter first resonant periods due to the restoration of the stiffness. In addition, the added damping of the repaired oil dampers and the replaced tin-rubber bearings unquestionably worked to suppress earthquake-induced vibrations of the structure.

To illustrate the effect of rubber bearings, another comparison was made between the states on 2011/03/09 (i.e., the undamaged state before the 3/11 Earthquake) and on 2013/08/04 (i.e., the retrofitted state). The transfer functions are pictured in Fig.12. It was found that the maximum amplification factors of the retrofitted states are less than those of the undamaged state for both observation and simulation. This result explains that the newly-installed isolators can dissipate more vibration energy than the original

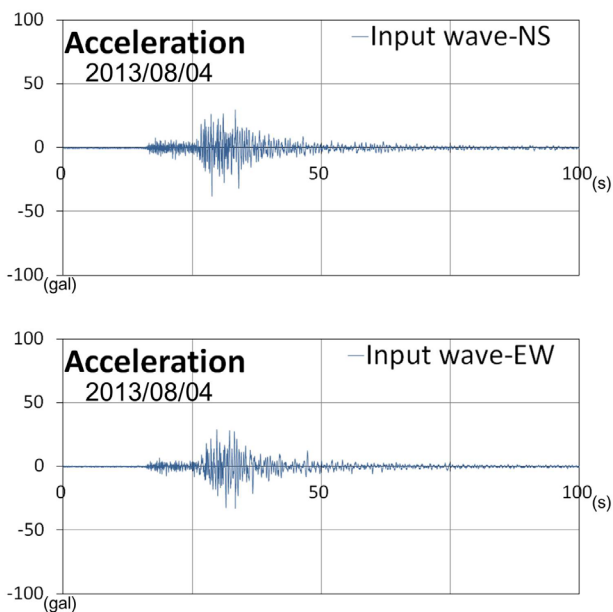


Fig.9. Ground Motion of 2013/08/04

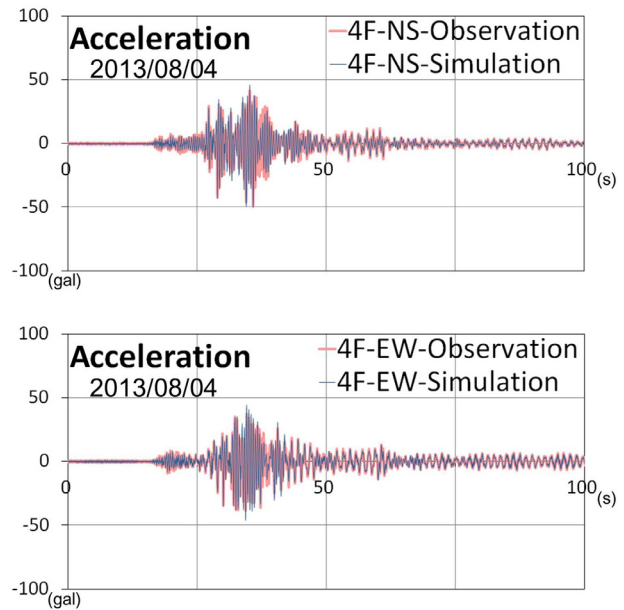


Fig.10. Acceleration Responses of Observation and Simulation (2013/08/04)

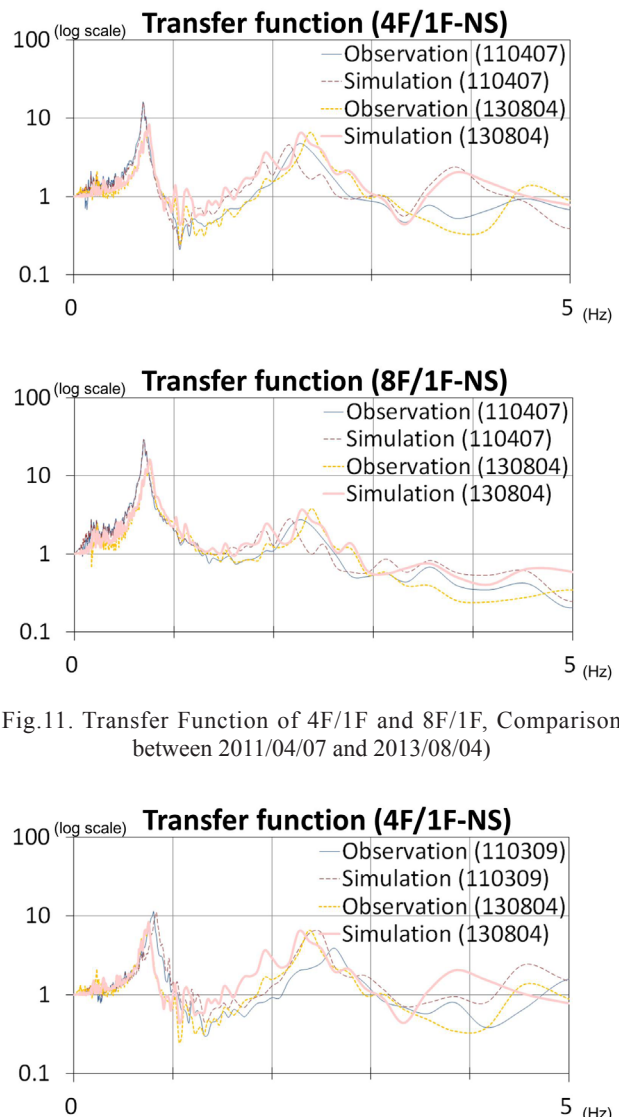


Fig.11. Transfer Function of 4F/1F and 8F/1F, Comparison between 2011/04/07 and 2013/08/04

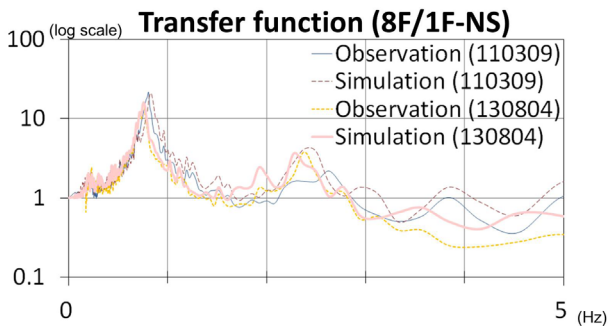


Fig.12. Transfer Function of 4F/1F and 8F/1F, Comparison between 2011/03/09 and 2013/08/04)

oil dampers for this steel building. After rehabilitation, the building with the rubber bearings has better earthquake resistance than the original damping system.

For each different state of this steel structure, the amplification coefficients at the 1st resonant frequency in NS direction obtained from the transfer function are plotted in Fig.13. The variation in the amplification coefficient shows a tendency to increase soon after the 3/11 Earthquake (which indicates reducing damping); in pace with the retrofitting, the amplification coefficients gradually reduced (indicating increasing damping) until the full retrofit was completed. It is

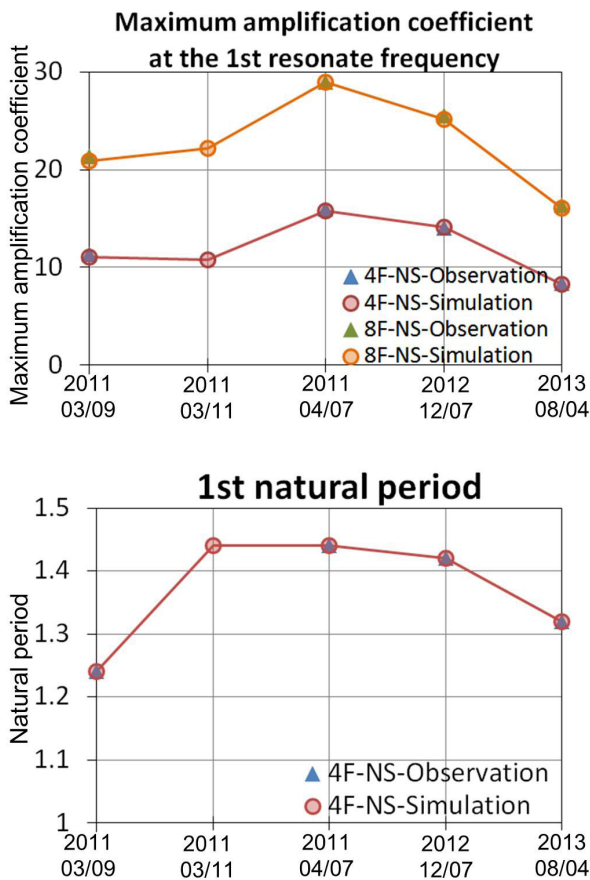


Fig.13. Dynamic Characteristics of the Steel Building in 5 Different States

important to indicate that the amplification coefficients of the 5th state were less than those of the 1st state, which means that the rubber bearings have an advantage over the oil dampers for this building in the aspects of the vibration control and the allowable deformation of the dampers. The 1st resonant period of each state in NS direction is shown in Fig.13.

7. Discussion of Performance of Energy Dissipation Devices

The retrofit strategy using rubber bearings proved to be successful based on the simulation and observation results. However, this retrofit plan was event oriented, and the design philosophy behind this procedure should be generalized for the rehabilitation of damaged or degraded passive-controlled structures.

In usual design practice, the target level of building performance should be selected by the performance-based design philosophy on the basis of the owner's demand or serviceability requirements before the design of a new passively controlled building or the retrofit of an existing building with energy dissipation devices. The target level of the building performance would prescribe the performance level for the respective structural and nonstructural components, including the damping system. As described in FEMA guidelines, the performance of the building can be categorized into four levels: Collapse Prevention, Life Safety, Immediate Occupancy and Operational (from the basic to enhanced levels). However, there is no performance requirement for the damping system. This section will discuss the performance of the energy dissipation devices during the rehabilitation design.

By providing an additional damping mechanism, passive energy dissipation devices are able to reduce the earthquake displacement in the structure. However, they have little effect in improving the structural capacity of force resistance because they do not add an extra path for resisting the external forces to the main frame of the structure.

The seismic rehabilitation design depends on the characteristics of the main structure, the properties of the device, and their connecting elements. For most structures with Collapse Prevention Building Performance Level for infrequent earthquakes, the building would experience plastic deformation due to the ductility requirement. If the connection of the damper and the structure is not the weak link in the system, it is likely to increase the force acting on the structural components during the yielding stage, and therefore, increase the risk of a structural component failure. The enhanced performance level of the energy dissipation devices will not improve the structural capability of collapse prevention.

Therefore, energy dissipation devices are mostly of limited use for ordinary structures with a basic performance level, as described in FEMA 273 (FEMA, 1997) and FEMA 356 (FEMA, 2000), "these devices

would be expected to be good candidates for projects that have a Performance Level of Life Safety, or perhaps Immediate Occupancy, but would be expected to have only limited applicability to projects with a Performance Level of Collapse Prevention".

On the other hand, for structures with an enhanced performance level, these devices are mandatorily required to sustain the maximum displacement or velocity induced by the maximum considered earthquake for avoiding connection failure. However, there is no current guideline that describes how to design the damper and the building when the structure is shaken by earthquakes beyond the considered level.

Learning from the severe failure event of the dampers during the 3/11 Earthquake, the researchers and engineers should realize that passive control dampers or their connectors could be damaged by major earthquakes beyond the considered level. Dampers are not designed to survive catastrophic earthquakes and could serve as the first defensive line of seismic protection. By acknowledging this fact, the remaining issues, which have not gained much attention, include the safety of the main frame without a damping system and the retrofit procedure after the failure or degradation of the damping devices. Furthermore, dampers and their connectors could be designed to have a corresponding performance level to a structure with an enhanced performance level, which requires the damping system to sustain a response with a different margin level for a maximum considered earthquake depending on the performance requirements of the building. These problems require further investigation and quantitative research in the future.

In this failure event, there was no other structural damage found in the main frame of this building after the 3/11 Earthquake other than the oil dampers. The building performance levels are the Immediate Occupancy level or the even higher Operational Performance level for an earthquake hazard level with the magnitude of the 3/11 Earthquake (the earthquake hazard level has a 2% of exceedance in 50 years). However, for the original oil dampers of this Administration Building, the performance is far below the building performance level required to function properly if the same magnitude earthquake occurs. Therefore, the target performance level for the energy dissipation dampers should be enhanced to achieve a better overall building performance. Apparently, the proposal to replace the damaged dampers with the same type was not convincing. The retrofit plan using tin rubber bearings capable of larger interstory drifts met the requirement for the enhanced performance and was proved to be superior.

8. Conclusion

This report presented a new way to utilize the energy dissipation capability of rubber or neoprene bearings for the seismic rehabilitation of damaged oil dampers without considering the bearings as vertical supporters to decouple the superstructure from the ground motion. From the rehabilitation process, some conclusions can be drawn:

1. For a steel structure with damaged oil dampers, a hybrid retrofit plan using bearings has been proposed because the retrofitted building with tin-rubber isolators has a better seismic performance than the one equipped with the original oil dampers, as exhibited by simulation and observation results;
2. The proposed hybrid concept for vibration control can provide a quick and less expensive retrofit strategy if the damping devices are damaged by a rare earthquake.

While the energy dissipation devices can suppress the vibration responses, they cannot enhance the load carrying capacity of the structures. After a quantitative analysis and intuitive decision making of the rehabilitation plan, what we have learned is that the target performance level of energy dissipation devices should be set based on the building performance level for the designs of seismic rehabilitation, which is missing in the current guidelines and design codes. In the near future, more efforts need to be spent in investigating the performance-based theory of the controlled high-rise structures and establishing the design and retrofit methodology of buildings which incorporate the idea of recoverable and replaceable dampers.

Acknowledgements

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